Meeting the Target Challenge

Experiments on the National Ignition Facility require innovative targets precisely centered inside the laser's target chamber.

THE National Ignition Facility (NIF) is a one-of-a-kind scientific laboratory, able to create the temperatures, pressures, and densities of an exploding nuclear weapon or the interior of a large planet such as Saturn. Scientists from around the world will soon put the powerful laser to work in the "X Games" of science, examining physical interactions that were previously impossible to replicate. (See the article on p. 4.)

One such "game" will tackle a scientific grand challenge: demonstrating thermonuclear ignition and gain on a laboratory scale. According to Ed Moses, associate director for Livermore's NIF Programs, the NIF team is committed to

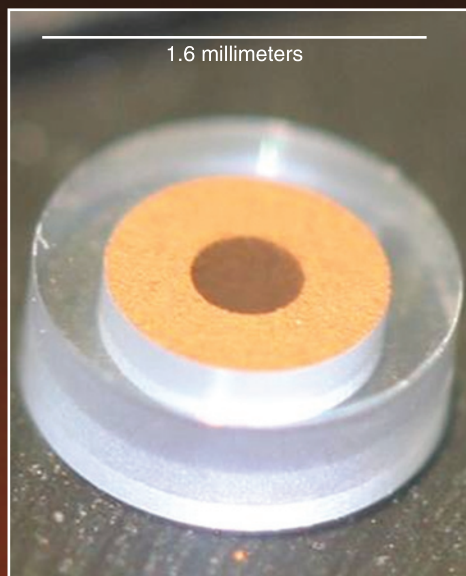
a credible attempt at inertial confinement fusion (ICF) by 2010. This effort is funded by the Department of Energy's National Ignition Campaign, whose goal is to transition NIF into a highly flexible high-energy-density science facility by 2013.

Experiments are also planned to assess the reliability of the nation's nuclear weapons stockpile in support of the National Nuclear Security Administration's Stockpile Stewardship Program. In addition, scientists will use the 192-beam laser to explore basic science research in an array of fields from radiation transport to materials dynamics, hydrodynamics, astrophysics, and nuclear physics.

All of these experiments have one common requirement: a miniscule target, precisely centered in the target chamber. Creating a NIF target is a complex interplay among target designers, materials scientists, and engineers. The designers understand the goals for each experiment and must establish target specifications accordingly. NIF targets are typically only a few millimeters in size, and they must be machined to meet precise requirements, including specifications for density, concentricity, and surface smoothness.

When a new material structure is needed, materials scientists create the essential raw materials. Fabrication engineers then determine whether those materials—some of them never seen before—can be machined and assembled. If the new materials pass muster, components or an entire target will be assembled for an experiment. (See *S&TR*, September 2006, pp. 23–25.)

Throughout the design process, engineers inspect the target materials and components using nondestructive characterization methods to ensure that target specifications are met and that all components are free of defects. Together, this multidisciplinary team takes an experimental target from concept to reality.



Livermore researchers have developed two materials to use in targets for the National Ignition Facility (NIF). The sample shown above is made of extremely low-density gold foam. Below and in the background are hollow capsules made of high-density carbon.

Targets for the ICF experiments are being fine-tuned by a large collaboration that includes scientists and engineers from Lawrence Livermore, Los Alamos, and Sandia national laboratories; the University of Rochester's Laboratory for Laser Energetics; and General Atomics in San Diego. This team is perfecting the target materials and methods to fabricate them. The team also is advancing laser-driver performance, designing new targets, and developing experimental characterization and diagnostic techniques. Jeff Atherton, NIF's deputy associate director for science and technology, leads the ICF target fabrication and materials team, which is using a target design by John Lindl, Steve Haan, Brian MacGowan, and their team of physicists in the Laboratory's Defense and Nuclear Technologies Directorate.

Another project team is synthesizing new materials and inventing fabrication techniques for different kinds of targets. Some of these will be used in fusion experiments to be conducted after the laser achieves ignition. Others will be needed for experiments to advance stockpile stewardship and basic science. Materials scientists and engineers from Livermore's Nanoscale Synthesis and Characterization Laboratory (NSCL), under the direction of scientist Alex Hamza, perform this work as part of a strategic initiative funded by the Laboratory Directed Research and Development Program. (See the box on p. 14.) Nanoscale materials developed

for NIF experiments include high-density carbon, very low-density copper and gold foams, and graded-density foams.

Manufacturing requirements for all NIF targets are extremely rigid. Components must be machined to within an accuracy of 1 micrometer, or one-millionth of a meter. Joints can be no larger than 100 nanometers, which is just 1/1,000th the width of a human hair. In addition, the extreme temperatures and pressures the targets will encounter during experiments make the results highly susceptible to imperfections in fabrication. Thus, the margin of error for target assembly, which varies by component, is strict.

New tools to image and characterize a material allow scientists to quantify its performance and determine how to improve its fabrication techniques. Computer simulations and experiments conducted at supporting facilities, such as Livermore's Center for Nondestructive Evaluation and the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics, also help researchers refine target designs and improve characterization and diagnostic capabilities.

The Demands of ICF

"The requirements for ignition targets are especially daunting," says Atherton. The current design for the ICF target is a copper-doped beryllium capsule with a smooth, solid layer of the hydrogen isotopes deuterium and tritium (D-T) on its inner surface. The radially tailored capsule fits inside a 9-millimeter-high by 5-millimeter-wide hohlraum cylinder made of a material with a high atomic number, such as gold.

When NIF's laser beams impinge on the hohlraum's inner cavity, laser energy is converted to x-ray energy. These x rays bathe the capsule and ablate its outer layer. Conservation of momentum requires that the remaining material implode. Compressing the D-T fuel to extraordinarily high temperature, pressure, and density ignites a burning hydrogen plasma.

The polished beryllium capsule designed for inertial confinement fusion experiments is 2 millimeters in diameter. The 10-micrometer fill tube attached to the top of the capsule is barely visible.

"The beryllium capsule must have a precise spherical shape for NIF to achieve ignition," says Atherton. The capsule's outer surface must be smooth to within 1 nanometer—an unprecedented requirement for surface roughness—and the thickness and opacity of the copper-doped layers must be carefully controlled. A hole less than 5 micrometers in diameter is drilled through the 150-micrometer-thick beryllium layer so the capsule can be filled with D-T gas. Simulations indicate that a fill hole this size will have only a small effect on the capsule's implosion.

Another challenge is ensuring the symmetry of the implosion. Experiments will require the target capsule to be placed within 8 micrometers of the center of the hohlraum, which is only 1 centimeter in diameter. Within 30 hours after the D-T gas is introduced, it is frozen on the capsule's inner surface, producing a smooth layer with a roughness of less than 1 micrometer.

Capsule Collaborators

To achieve the daunting specifications for ICF targets, Livermore researchers are working closely with scientists at other

The Nanoscale Synthesis and Characterization Laboratory

Lawrence Livermore established the Nanoscale Synthesis and Characterization Laboratory (NSCL) in 2004 to advance interdisciplinary research and development opportunities in nanoscience and nanotechnology in support of the Laboratory's national security mission. NSCL brings together experts from Livermore's Chemistry, Materials, and Life Sciences (CMLS) and Engineering directorates. It also fosters collaborations with researchers from other institutions. Alex Hamza of CMLS leads NSCL, and the deputy director is Don Lesuer from Engineering.

NSCL research focuses on the change in behavior that may occur when the size of a material's property-controlling structure shrinks to a few nanometers. For example, some nanometer-scale materials are extremely strong. NSCL researchers work to apply the unusual properties of nanoscale materials to develop technologies for national security. One important research area is fabricating targets for the National Ignition Facility and other stockpile stewardship experimental platforms.

NSCL's long-term research goal is to thoroughly understand materials at the nanoscale. Researchers want to determine how a material's properties and behavior change at the nanoscale and how best to fabricate nanoscale devices. With this knowledge, scientists can then assemble structures smaller than 100 nanometers and manipulate the materials to optimize their performance. NSCL's research focuses on four science and technology areas: nanoporous materials, advanced nanocrystalline materials, three-dimensional nanofabrication technologies, and nondestructive characterization.

institutions in the U.S. and Europe. For example, Laboratory scientists Steve Letts, Suhas Bhandarkar, and Andrea Hodge are working with General Atomics researchers Abbas Nikroo and Andrew Forsman to develop the beryllium capsules.

Each capsule is made by depositing beryllium on a smooth, perfectly spherical plastic mandrel. As the mandrel is rotated, a 150-micrometer-thick layer of beryllium slowly builds up on its surface. After a capsule is polished, a laser is used to drill a fill hole. An oxidation technique removes the mandrel through the drilled hole, and a 10-micrometer tube is attached to the capsule so it can be filled with D-T gas.

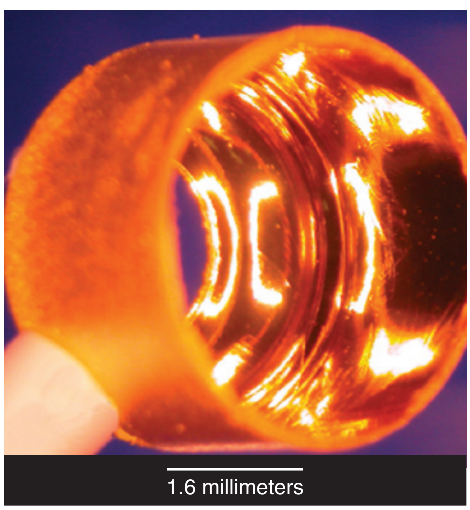
An alternative design to the beryllium capsule uses high-density carbon, which, like beryllium, has a low atomic number. Its higher density (3.5 grams per cubic centimeter) makes it an attractive material for an ICF capsule. Laboratory chemist Juergen Biener is working with researchers at the Fraunhofer Institute for Applied Solid-State Physics in Freiburg, Germany, to implement this design. The Fraunhofer team has developed techniques to deposit high-density carbon films on 2-millimeter silicon mandrels, polish the spheres, and remove the silicon mandrel. The mandrel is removed by etching through the laser-drilled hole where the fill tube will be attached. Livermore is responsible for developing the techniques to fill the shell with fuel.

Fabricating the cylindrical hohlraum is another challenge. Nikroo, Heather Wilkens, and other researchers at General Atomics have developed fabrication techniques that couple as much laser energy to the capsule as possible. Their 7-micrometer-thick hohlraum is made with layers of gold and uranium sputter-deposited on a precision-machined mandrel. (See the figure below left.) After deposition, the mandrel is leached away. Because uranium is highly reactive in the presence of oxygen and water vapor, gold must encapsulate the uranium layers.

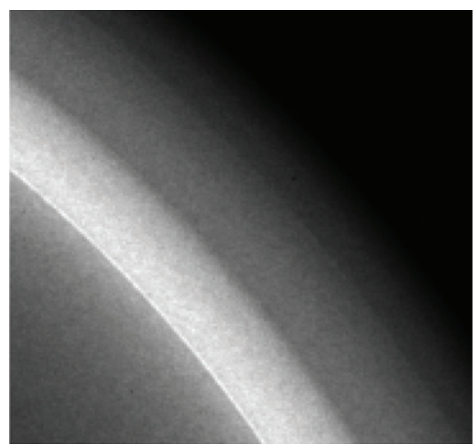
Fuel Chills Out

Laboratory scientists John Moody, Evan Mapoles, and Bernard Kozioziemski have pioneered procedures to form the frigid layer of D-T fuel inside the fuel capsule. The D-T ice is 1.5 degrees below the triple point of the hydrogen isotope mixture—the temperature at which all three phases of the substance can coexist in equilibrium. Temperature can fluctuate no more than 1 millikelvin—a demanding requirement for accuracy. “Understanding the science of D-T layer formation is critical for the ignition experiments,” says Kozioziemski, “and an extremely exciting endeavor.”

Beta decay of the tritium helps smooth the layer by selectively heating thicker regions and evaporating hydrogen from them. NIF researchers found that the D-T ice can be shaped by precisely controlling heat transfer within the hohlraum, including contributions from thermal convection of helium. Auxiliary heaters located on the hohlraum shape the temperature field within the target to produce a nearly spherical isotherm. To control the ice layer’s surface roughness, the NIF team developed a seeding and cooling protocol. The seeding process forms the initial layer, and cooling reduces its temperature from the triple point. With this protocol, the team achieved a



A hohlraum is the metal case that holds a fuel capsule for NIF experiments. Shown here is one-half of a gold–uranium hohlraum after the mandrel has been removed.



This digital x-radiograph shows a high-density carbon capsule with an inner layer of frozen deuterium–tritium fuel. The capsule’s inner diameter is 2 millimeters. The fuel layer is only 50 micrometers thick, and its surface roughness is a mere 0.5 micrometer.

roughness of about 0.5 micrometer (root mean square) at the interface where solid D-T meets D-T gas.

Livermore engineers Beth Dzenitis and Jeff Klingmann are developing procedures to mount the capsules and control the cryogenic temperature. For this operation, the capsule is “tented” between polymer sheets held in place by the two sides of the hohlraum. A thermomechanical package encases the hohlraum to control the position and temperature of the hohlraum–capsule assembly.

The thermomechanical package is a modular design with a precisely fabricated aluminum structure on each end. A band in the middle of the package has cutouts to accommodate the shot diagnostics. Silicon “arms” attached to each end of the package conduct heat from the hohlraum. These lithographically etched support arms create a heat-transfer path that ensures temperature uniformity in the target. In addition, a flexure coupling between the silicon arms and the aluminum structure accommodates differential thermal contraction.

With the thermomechanical package, the target assembly can maintain its position to within 2 micrometers, and at 18 to 20 kelvins, temperature fluctuations are limited, as required, to 1 millikelvin. “This is a novel approach to target engineering,” says Dzenitis, “designing both for manufacturability and reproducibility.”

Laboratory researcher Terry Malsbury leads the NIF team responsible for developing the cryogenic target-positioning system. This system integrates the ICF target with a cryogenic layering and characterization station and a target positioner attached to NIF’s target chamber. The system includes a positioning boom to center the target in the chamber. An ignition-target inserter cryostat attached to the positioner cools the target and the D-T fuel to meet temperature and uniformity requirements. The layering and characterization station can image the D-T fuel layer in three directions within a few minutes.

Targets in a Lather

Livermore scientists are experimenting with a variety of extremely low-density foams. For example, copper foams will be used to explore high-energy-density science and advanced fusion concepts, and nanoporous gold foams are being developed for hohlraums.

Octavio Cervantes, a materials scientist in the Chemistry, Materials, and Life Sciences Directorate, has upgraded a process designed to build copper foam with pores smaller than 1 micrometer in diameter. To make the foam, Cervantes

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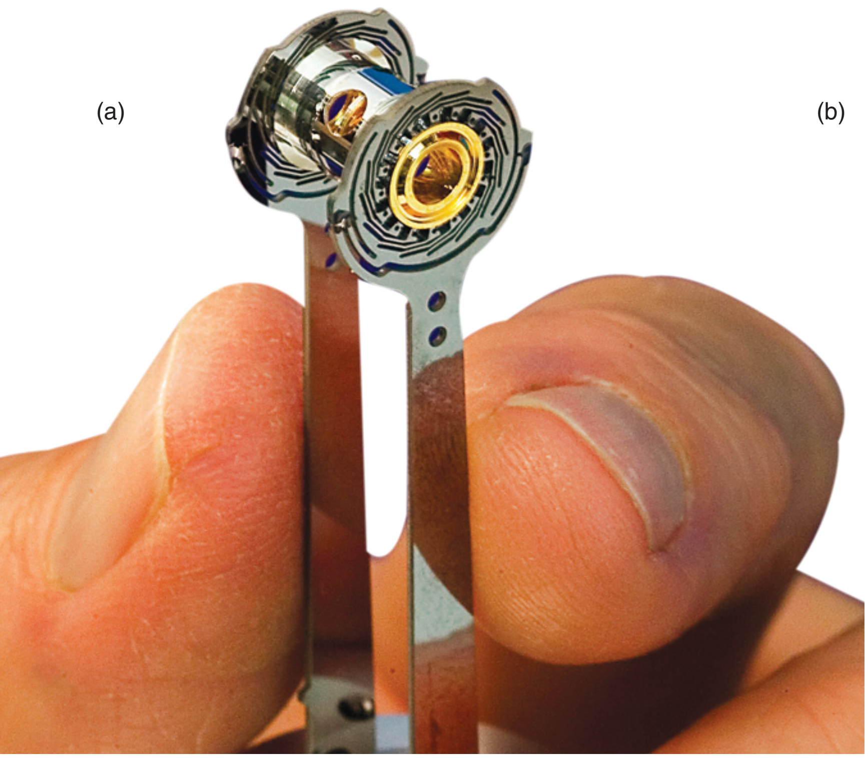

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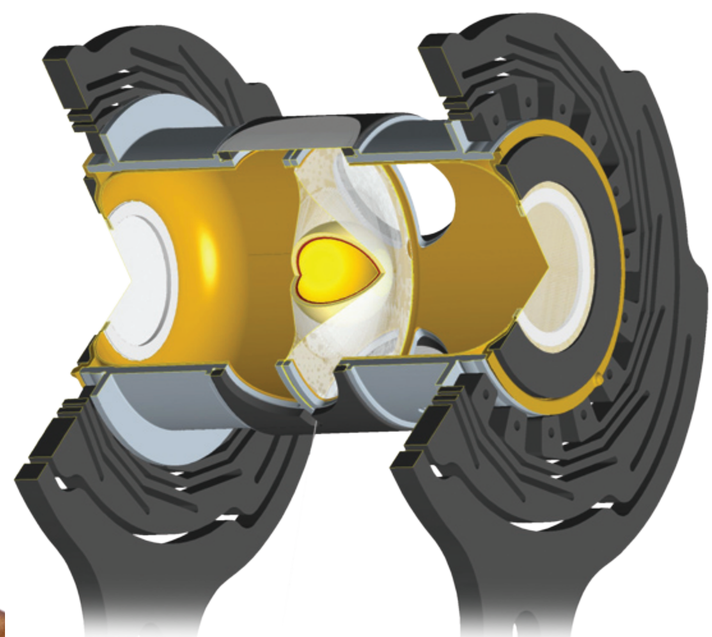


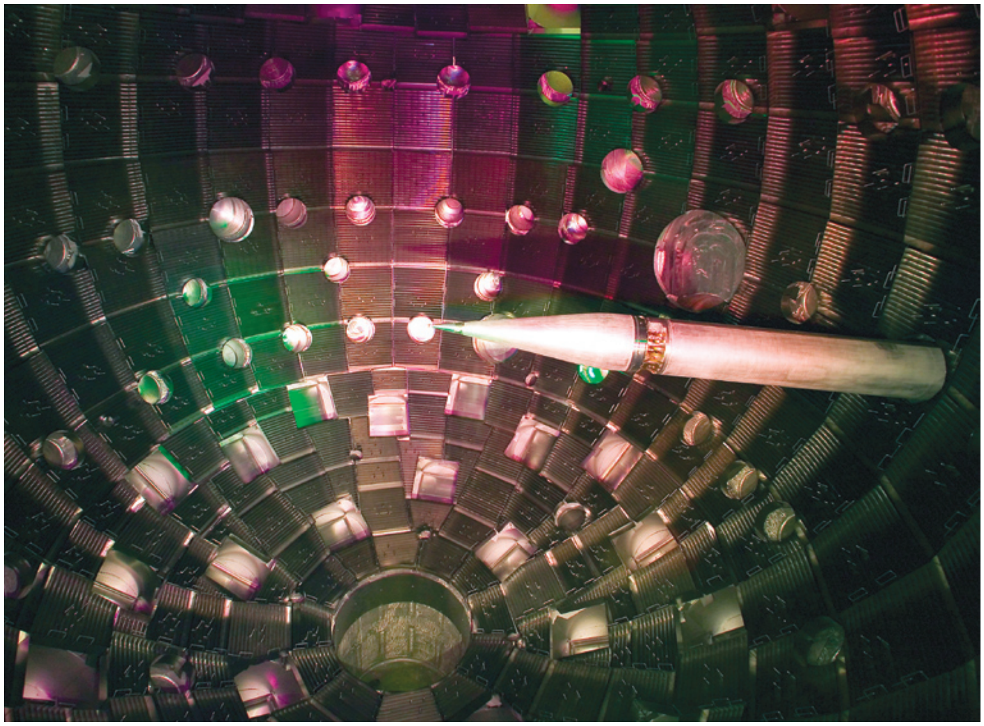
(a) The thermomechanical package for the hohlraum–capsule assembly has a 2-millimeter-diameter capsule in the center.
(b) A cutaway rendering of the package shows the tenting of the capsule and the silicon support arms.

pours a solution of water, copper nanoparticles, and polystyrene spheres onto a water-absorbing medium. As the water is absorbed, the copper particles are deposited onto the medium's surface, forming a uniform monolith. Annealing the monolith burns off the polystyrene, leaving behind the copper foam.

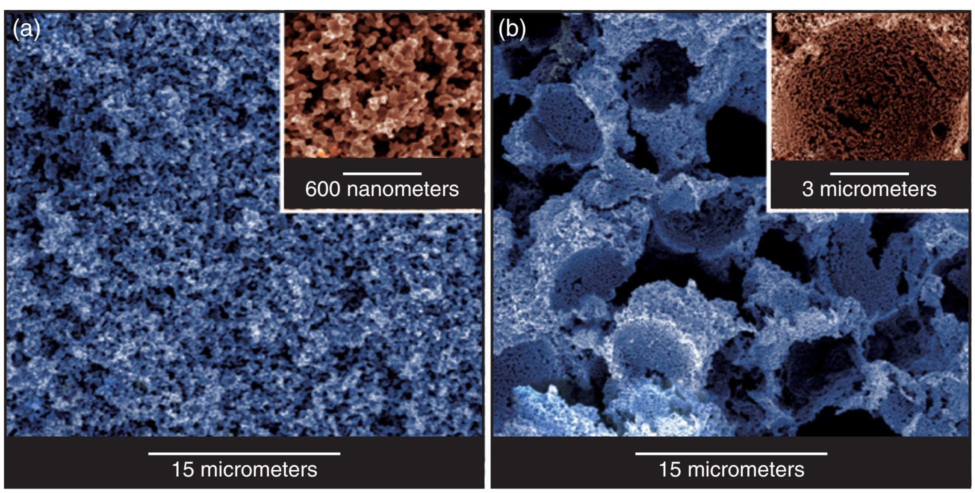
Polystyrene spheres 1 micrometer in diameter produced foam with a relative density of 15 percent. A mixture with spheres between 0.5 and 1 micrometer could potentially decrease the foam's density to 10 percent, or 890 milligrams per cubic centimeter. The foam is extremely light yet strong enough to be machined into simple structures such as small disks and hollow cylinders. Researchers at the Center for Nondestructive Characterization are developing laser-based ultrasonic methods to measure the foam's mechanical properties.

The path to designing nanoporous gold foams has been more circuitous. Livermore chemist Greg Nyce tried coating polystyrene beads with gold and casting them into a monolith mold in a process similar to that used by Cervantes. When the mold was heated, however, some of the hollow gold spheres contracted, which increased the gold's relative density to 20 percent instead of the 1 to 2 percent required for the NIF targets.

One method proposed to solve this problem is dealloying. In this process, polystyrene beads are coated first with a layer of gold and then with a layer of silver. Heating the monolithic structure to more than 670 kelvins removes the beads and produces hollow silver-and-gold shells. The shells are then exposed to nitric acid to remove the silver, leaving a shell of nanoporous gold. The dealloyed foams have a relative density of 2 percent, or 400 milligrams per cubic centimeter—a significant reduction for gold particles, which at full density weigh 19.3 grams per cubic centimeter.



Before each NIF experiment, a positioner precisely centers the miniscule target inside the target chamber. In inertial confinement fusion experiments, the target-positioning system will integrate the target with a cryogenic layering and characterization station and a target positioner.



Scanning electron microscope images show how polystyrene beads in copper foams create empty space, which reduces a material's density. (a) A foam with no beads has a relative density of 25 percent. (b) Using beads 10 micrometers in diameter reduces the foam's relative density to 10 percent. Insets show micrographs at high resolutions.

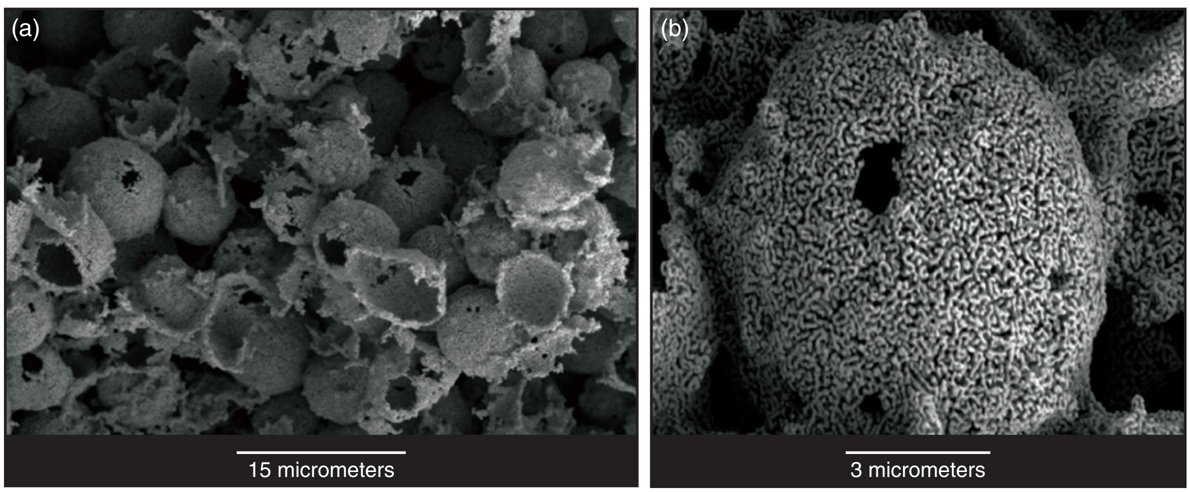
"The product is very fragile," says Nyce, "but it can be machined." Nyce recently received a Nano 50 Award from *Nanotech Briefs* for the gold foams, which are fabricated with 500-nanometer shells.

Varying Foam Densities

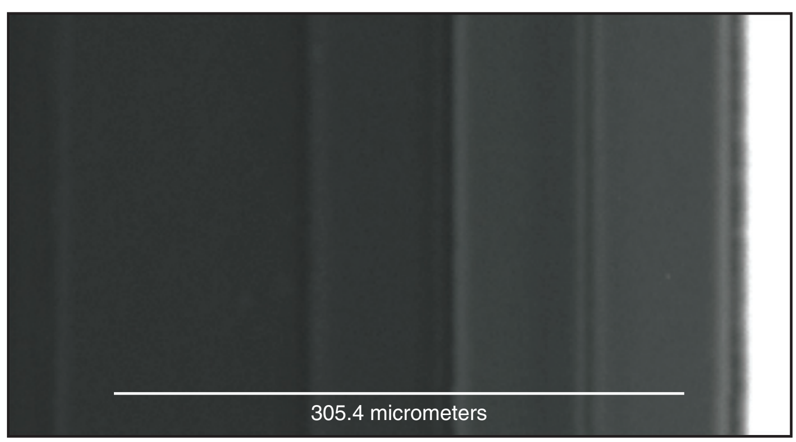
Another target design uses graded-density foams. In a high-energy-density experiment, a laser such as NIF can slam into a graded-density target without creating a shock, allowing researchers to determine a material's strength under high pressure and density but low temperature. (See *S&TR*, March 2007, pp. 23–25.) These foams can also be layered with varying density gradients to tailor the shock delivered to the material being studied. Target designers want graded-density foams about 0.5 millimeter thick, with the highest density material tapering off to zero density. (See the bottom figure below.)

To develop these novel materials, a team of chemists led by Joe Satcher is experimenting with carbon aerogels of various densities. For this project, Livermore engineer George Langstaff and machinists on the target fabrication team produce aerogel slabs each about 50 micrometers thick. Satcher's team then bonds the slabs together using a silica aerogel "glue" that is barely denser than air. This method can produce stepped-gradient structures up to 0.5 millimeter thick, with density gradients tailored to meet experimental requirements.

Livermore engineer Robin Miles and her team have had some success making graded-density foams with proximity nanopatterning, a technique pioneered by John Rogers at the University of Illinois.

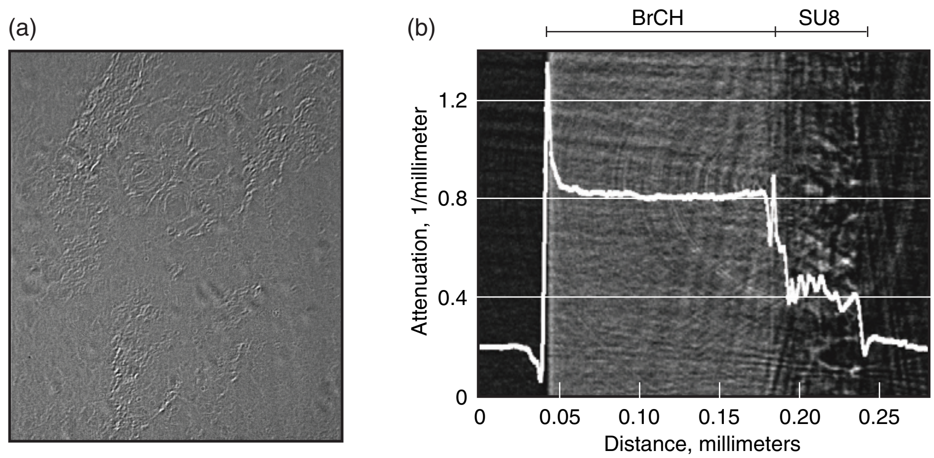


Scanning electron micrographs of porous gold (a) before and (b) after dealloying show how this process changes a material's density.



This micrograph shows a graded-density structure made of carbon aerogel bonded with a silica aerogel "glue" that is barely denser than air.

With this technique, they can design a structure so that density decreases continuously from end to end. Miles's team tailored a graded-density foam that absorbs light in SU8 while imprinting a nanostructure from an elastomeric mask. This structure grades from full density to 5 percent relative density. (See the figure at right.) The films developed to date are 80 to 100 micrometers thick. Says Miles, "Scaling up to a thickness of 500 micrometers is the next challenge."



(a) A digital radiograph provides a planar view through a graded-density target made of a brominated polystyrene (BrCH) substrate with 60 layers of a photopolymer (SU8). The density of SU8 changes from full density to 5 percent relative density with each 1-micrometer layer. (b) A computed tomography cross section of the target with a profile overlay shows the layer-by-layer decrease in density.

Final Evaluation

Nondestructive characterization—a technique for inspecting materials without damaging them—is a key tool for evaluating the complex, fragile materials used in NIF targets. The resulting data allow researchers to predict a material's performance, examine its structure, and model its behavior. Livermore scientist Harry Martz and his team are responsible for developing the nondestructive techniques needed to evaluate the NIF targets. Martz is also working with fabrication engineer Matthew Bono to design methods for handling and holding the tiny, delicate components.

Peering inside optically opaque materials requires penetrating x rays, acoustic waves, or particles. Livermore's x-ray computed tomography system images materials with a resolution of less than 1 micrometer over a 1-millimeter field of view. Another evaluation technique is synchrotron radiation, which produces x-ray microdiffraction images showing a material's structure.

Kozioziemski, Martz, and others used phase-contrast enhanced x-ray imaging to examine the D-T layer in a beryllium fuel capsule. (See the bottom right figure on p. 15.) Absorption x-ray imaging cannot distinguish the layers clearly enough because the capsule materials have such a wide range in opacity—the D-T fuel is 10,000 times less opaque than the shell. However, the phase-contrast technique produced the first images of the solid D-T fuel layer inside a copper-doped beryllium shell. Precision radiography can also detect opacity fluctuations buried in the beryllium shell.

"Graded-density materials are especially difficult to study and interpret," says Martz. One characterization method tried by his team combines digital x-radiography and computed tomography. Distortions called phase effects at material boundaries make it challenging to measure the gradient. Computer simulations indicate that acoustic microscopy may be a better diagnostic method. When surface acoustic waves propagate through a multilayered material, the pattern of propagation across the surface varies with density. "Gigahertz frequencies can yield micrometer spatial resolution in millimeter-size samples," says Martz, "which is the level of detail we need."

Targets for Science

Lawrence Livermore has a long history of developing new materials, fabrication techniques, and characterization and diagnostic methods to address the important national problems it is asked to solve. From miniaturizing nuclear weapons in the late 1950s to proving fusion ignition on a laboratory scale five decades later, Livermore's can-do attitude consistently meets with success.

Livermore researchers are already using the expertise developed in designing NIF targets to support the Department of Energy's high-energy-density science mission. The experience gained from that work will no doubt be applied in some future, as yet unknown scientific endeavor.

—Katie Walter

Key Words: beryllium capsule, Center for Nondestructive Characterization, cryogenics, high-density carbon, ignition target, inertial confinement fusion (ICF), metallic foam, nanoporous material, Nanoscale Synthesis and Characterization Laboratory (NSCL), National Ignition Facility (NIF).

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